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Stability of nano-scaled Ta/Ti multilayers upon argon ion irradiation

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ABSTRACT

The effects of argon ion irradiation on structural changes in Ta/Ti multilayers deposited on Si wafers were investigated. The starting structures consisted of sputter deposited 10 alternate Ta (~23 nm) and Ti (~17 nm) layers of a total thickness ~200 nm. They were irradiated at room temperature with 200 keV Ar^+, to the fluences from 5×10^{15} to 2×10^{16} ions/cm^2. The projected ion range was around mid-depth of the multilayered structure, and maximum displacements per atom ~130. It was found that, despite of the relatively heavy ion irradiation, individual nanocrystalline Ta and Ti layers remain unmixed, keeping the same level of interface planarity. The changes observed in the mostly affected region are increase in lateral dimensions of crystal grains in individual layers, and incorporation of bubbles and defects that cause some stretching of the crystal lattice. Absence of interlayer mixing is assigned to Ta–Ti immiscibility (reaction enthalpy $\Delta H_f = +2$ kJ/mol). It is estimated that up to ~5 at.% interface mixing induced directly by collision cascades could be compensated by dynamic demixing due to chemical driving forces in the temperature relaxation regime. The results can be interesting towards developing radiation tolerant materials based on multilayered structures.

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1. Introduction

Nano-scaled multilayered thin films are interesting for wide application, due to their specific properties compared to single component systems [1]. One promising field is the development of radiation tolerant materials, taking the advantage of multiple interfaces that contribute to reduce the effects of accumulated radiation damage [2–6]. Defects induced by energetic particles affect the performance of such materials in radiation environment [6–8]. Among multilayers, those composed of immiscible materials are particularly interesting, because chemical driving forces can prevent a considerable radiation induced atomic intermixing at the interfaces. Ion irradiation stability was reported for immiscible metallic multilayers, such as Cu/Nb [2,3], W/Ni [9], Cu/W [10] and Mo/Cu [11], and more recently for immiscible ceramic (metal-nitride) systems [12,13]. In general, ion irradiation is a powerful technique for achieving solid solutions or metastable alloying in non-mixing materials, due to its non-equilibrium nature. The process involves ballistic mixing [14] due to atomic collision cascades and thermal spikes [15] that develop around the ion tracks in many inert gas ion–metallic target combinations, where the energy transfer and local temperature quenching are probably most rapid among the currently available processing techniques. A collision cascade lasts typically ~10^{-13} s, the period for equalizing the local temperature with the surroundings after a thermal spike is ~10^{-10}–10^{-9} s, the cooling rate is as high as ~10^{13-14} K/s. In this rapid thermalizing regime, chemical affinity of the constituents plays a dominant role on interface mixing [15]. Investigations of ion irradiation induced amorphous metallic-glass formation have shown that suitably designed very thin (a few nm) immiscible metallic multilayers can become totally intermixed and transformed to an amorphous phase [16]. For example, such behavior was observed in the immiscible Ta–Ti multilayered system (which has a positive reaction enthalpy ΔH_f) that was studied here. The chosen thickness of individual Ta and Ti layers (1.3–5.0 nm), and heavy Xe^+ ion irradiation forced a thorough intermixing which resulted in rapidly quenched amorphous and metastable crystalline Ta–Ti phases [17,18].

In this work we chose thicker individual Ta (~23 nm) and Ti (~17 nm) layers, and used Ar^+ ions for irradiation. The projected ion range was about mid-depth of the multilayered structure, the ions crossing several interfaces before coming to rest. The aim was not to cause a complete intermixing already in the collision cascade stage, but to study the contribution of other effects on ion irradiation stability of this immiscible system. In that sense,

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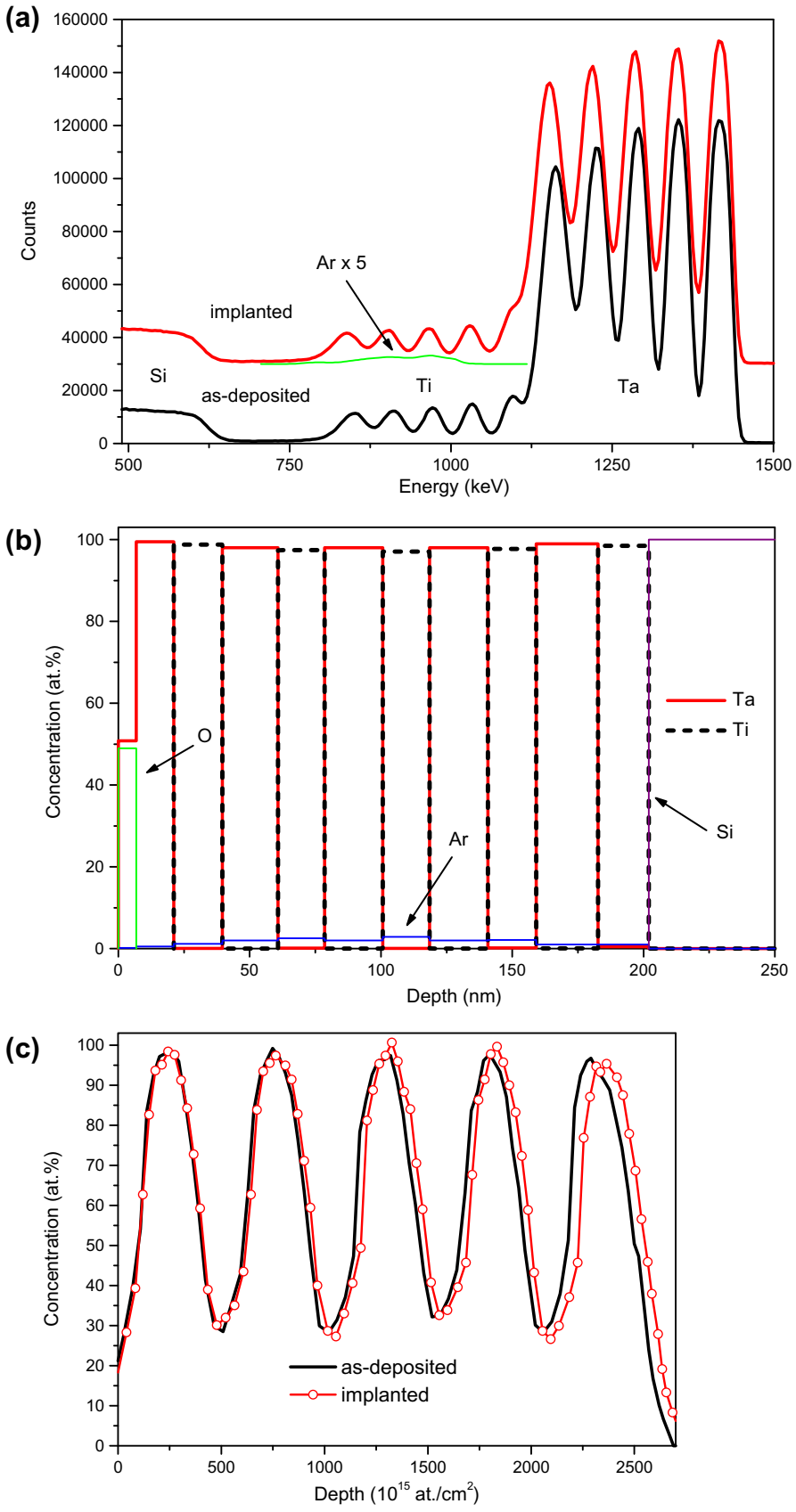

Fig. 1. RBS analysis of as-deposited Ta/Ti multilayers and irradiated with argon to 2×10^{16} ions/cm^2: (a) experimental spectra (fitted Ar yield multiplied by 5); (b) best fitted structure for the implanted sample; (c) extracted point to point Ta depth profiles.

well separated interfaces were selected to prevent a considerable cross-over of knocked-on atoms across entire individual layers. The applied ion mass, energy and fluence were sufficient to induce a considerable or complete mixing in many soluble or chemically

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